all of the uncertainty that is inherent in restoring and managing such a large, diverse, complex, and variable natural system. Ecosystem processes, habitats, and species are continually modified by changing environmental conditions and human activities; consequently, it is impossible to predict exactly how the Bay-Delta will respond to implementation of the ERP and other CALFED components. Restoring and managing the Bay-Delta ecosystem requires an approach that acknowledges the uncertainty in both the dynamics of complex systems and the effects of management interventions.

Holling (1998) classifies the practice of ecology according to two cultures, a dichotomy that can also describe the management of ecological systems. The first, traditional culture, is analytical and based on formally testing hypotheses to assess single causative relationships and attempting to find the single correct answer to questions and the single correct approach to solving problems. The second culture is integrative and exploratory, based on a comparative analysis of multiple hypotheses and an acknowledgment of uncertainty in management. Previous management of the Bay-Delta system has proceeded according to the first set of cultural practices. That is, historically, we have disregarded most of this complexity in resource management and treated such problems as though they were well defined in time and space and amenable to analysis (understanding) and remediation by standard methods. As failures in resource management based on this approach have become more visible and more serious, resource managers have shown increasing interest in methods that explicitly recognize the uncertainty inherent in management actions (Holling 1998). A suite of techniques collectively termed "adaptive environmental assessment and management," or simply "adaptive management," (Holling 1978, Walters 1986) has been adopted by several state and federal resource agencies as a practical approach to management under uncertainty.

According to Walters (1986), designing an adaptive management strategy involves four basic issues:

1. bounding the management problem in terms of objectives, practical constraints on action, and the breadth of factors to be considered in designing and implementing management policy and programs;

2. representing the existing understanding of the system(s) to be managed in terms of explicit models of dynamic behavior that clearly articulate both assumptions and predictions so that errors or inconsistencies can be detected and used as a basis for learning about the system;

3. representing uncertainty and how it propagates through time and space in relation to a range of potential management actions that reflect alternative hypotheses about the system and its dynamics; and

4. designing and implementing balanced management policies and programs that provide for continuing resource production while simultaneously probing for better understanding and untested opportunity.

Put another way, adaptive management involves: 1) having clear goals and objectives for management that take into account constraints and opportunities inherent in the system to be managed; 2) using models to explore the consequences of a range of management policy and program options in relation to contrasting hypotheses about system behavior and uncertainty; and 3) selecting and implementing policies and programs that sustain or improve the production of desired ecosystem services while, at the same time, generating new kinds of information about ecosystem function.

Reducing Uncertainty by Learning from Restoration and Management Actions

Restoring and managing the Bay-Delta ecosystem requires a flexible management framework that can generate, incorporate, and respond to new information and changing Bay-Delta conditions. Adaptive management provides such flexibility and opportunities for enhancing our understanding of the ecosystem. Within an adaptive management framework, natural systems are managed in such a way as to ensure their recovery and improvement while simultaneously increasing our understanding of how they function. In this manner, future management actions can be revised or refined in light of the lessons learned from previous restoration and management actions.

The key to successful adaptive management is learning from all restoration and management actions. Learning allows resource managers and the public to evaluate and update the problems, objectives, and models used to direct restoration actions. Subsequent restoration actions can then be revised or redesigned to be more effective or instructive. In an adaptive management process, learning must be continuous so that ecological restoration continuously evolves as the ecosystem responds to management actions and to unforeseen events, and as management actions are revised in light of new information. Without effective learning, ineffective management programs are likely to be perpetuated, unanticipated successes will go unrecognized, and resources will not be efficiently allocated.

To facilitate learning, adaptive management emphasizes the use of the scientific method to maximize the information value of restoration and management actions. Resource managers explicitly state hypotheses about ecosystem structure and function based upon the best available information, and then they design restoration actions to test these hypotheses. In this respect, adaptive management treats all management interventions as experiments. This does not suggest that management interventions are conducted on a trial-and-error basis, because management actions are guided by the best understanding of the ecosystem at the time of implementation.

Adaptive management is analogous to the "clinical trial" in medicine. In a clinical trial, a new therapy is tested on many patients, the trial is carefully monitored, and the progress of the trial is evaluated at regular intervals to determine whether to continue with the trial, abandon the trial, or declare the new therapy a success. Clinical trials are not initiated unless there is a reasonable expectation of success. Similarly, CALFED will not initiate large-scale ecological restoration unless there is a reasonable expectation of success.

By treating interventions as experiments, resource managers ensure that management is as efficient and successful as possible in achieving its objectives—unsuccessful interventions will not be perpetuated or expanded and successful interventions can be modified to use resources efficiently (e.g., land, water, tax dollars). Designing management interventions as experiments can have significant benefits when it comes to evaluating success or failure, increasing understanding of system dynamics, and making better decisions in the future (Walters et al. 1988 and 1989, Walters and Holling 1990). In adaptive management, treating interventions as experiments involves:

- making management decisions based on the best available analyses and modeling of the system;
- being clear about what management intervention is expected to achieve in terms of restoring ecological structure and function and the implications for species conservation;
- designing management intervention to help distinguish among alternative hypotheses about ecosystem behavior, where practical and compatible with the long-term goals of the program; and
- monitoring the effects of management intervention and communicating the results widely so that progress relative to expectations can be evaluated, adjustments made, and learning achieved.

As in clinical trials, an adaptive management program should incorporate Bayesian statistical techniques to judge progress and update probabilities among competing hypotheses. These techniques differ from the traditional hypothesis-testing approaches that play such a dominant role in ecological practice. Bayesian techniques are used to determine the probability that a hypothesis is true given the available information; when more than one hypothesis is proposed, probabilities can be compared among hypotheses. Decision rules can therefore be built into the program that are more socially and ecologically relevant than the 0.05 significance criterion commonly used in ecology. This approach is more in keeping with the notion of the second alternative culture of ecology (Holling 1998).

MODES OF ADAPTIVE MANAGEMENT

Walters (1986) recognized three approaches to management:

- **TRIAL-AND-ERROR**, in which early management options are chosen at random and later choices are made from a subset of the early options that performed best;

- **PASSIVE ADAPTIVE**, in which a best management option is chosen on the basis of the current beliefs about system dynamics and this option is fine-tuned in relation to experience; and

- **ACTIVE ADAPTIVE**, in which two or more alternative hypotheses about system dynamics are explored through management actions.

TRIAL-AND-ERROR MANAGEMENT. The first approach is illustrated by early attempts at stream habitat rehabilitation in which alterations were made to streams, and those that proved successful (e.g., stayed in the stream, attracted fish) became favored interventions. Some element of trial-and-error is a part of virtually every management policy.

PASSIVE ADAPTIVE MANAGEMENT. Passive adaptive management is perhaps the most common form of management intervention these days. It is highly defensible in that the best management action is chosen based on the best available scientific information (although which information is best may be subject to debate). It fits well with the incremental remedial approach to policy evolution that is common to public agencies (Lindblom 1959). It is administratively simple because all "units" are treated alike, and information needs and information management are relatively simple. Learning about the system using this approach, however, is confined to a very narrow window, and there is practically no possibility of determining whether the underlying hypothesis about the system is right or wrong; therefore, although passive adaptive management takes uncertainty into account, it has only limited capacity to reduce uncertainty.

Many elements of the ERP may have to be implemented as passive adaptive projects. Passive adaptive management may be dictated because the value of knowing that option A is a better description of system dynamics than option B is less than the cost of obtaining the information, or the alternative action poses too great a threat to public safety or valuable infrastructure, or for a variety of other reasons. Despite its limitations as a tool for learning about the system, a properly designed passive adaptive experiment can provide important insights into workable, if not optimal, solutions.

Unfortunately, strict adherence to experimental protocols is impossible in such a large-scale, passive adaptive program such as the ERP. There is, after all, only one Bay-Delta system, and its various component parts are all strongly interconnected. Independent replication of control and treatment measures is impossible in either space or time, violating an important principle of experimental design. The degree to which cause and effect can be determined should be tempered by this unavoidable limitation. All manipulations within the ERP should be based on careful and creative design to enhance the opportunity for learning and an analytical program that will allow as much distinction between confounded effects as possible.

ACTIVE ADAPTIVE MANAGEMENT. Active adaptive management is the most powerful approach for learning about the system under management but also is often the most contentious. Active adaptive management programs can create the false impression that managers or scientists are going to toy with the resources on which other people's livelihoods depend. Nevertheless, there is an important role for active adaptive management in the ERP, notwithstanding the critical status of many of the species the ERP is intended to benefit. It is important to realize that the purpose of active adaptive management is not to push the system to its limits and see how it responds. Rather, the purpose is to use management as a tool to generate information about the system when the long-term value of the information clearly outweighs the short-term costs of obtaining it.

It may be useful to distinguish between two kinds of active adaptive management. For many situations, it may be clear what kind of intervention is needed (e.g., increased spring and summer flows into the Delta for salmonid conservation), but the magnitude of the intervention is uncertain. The concern is not with the form of the model relating flow to conservation, but with the parameters of the model. An active adaptive management experiment could be designed to improve the estimation of parameters by manipulating spring and summer flow in appropriate ways. For purposes of this discussion, this kind of adaptive experiment will be referred to as "adaptive probing". In some instances, adaptive probing can be designed around natural fluctuations in environmental variables. A good example is the experiment conducted to improve estimates of optimal sockeye salmon escapement to the Fraser River. The principal issue was the level of escapement that would maximize yield to the fishery. The benefit-cost ratio of the experiment to test the benefits of higher escapements was very high, but involved fishers foregoing catch to achieve higher escapements in the short term. The experiment was initiated in the 1980s with very positive results in terms of yields in the late 1980s and early 1990s. Another example of adaptive probing is the Vernalis Adaptive Management Program (VAMP) which is designed to improve the scientific basis for the protection of San Joaquin fall-run chinook salmon smolts during their migration through the Delta. The program is based on a conceptual design which is to test the hypotheses related to smolt survival from five sets of San Joaquin inflow and Delta export levels.

In other instances, the greatest uncertainty may be about the best kind of intervention. For example, which would be the management action for spring-run chinook: increased spawning escapement or reduced cross-channel transport? In this case, the concern is with the form of the model (although obviously the size of the intervention is also important). Again, an adaptive probing experiment could be designed to determine which model (escapement or Delta transport) was the more important in chinook conservation. For purposes of this discussion, experiments designed to distinguish among fundamentally different models (hypotheses) will be referred to as "adaptive exploration." The Bay-Delta ecosystem is replete with such unresolved alternatives. To the extent feasible, the ERP will capitalize on opportunities to distinguish among such alternatives through active adaptive experimentation. Tools for assigning probabilities to models and updating probabilities in the light of new information, as well as rules for efficient design of adaptive experiments, are provided in Walters (1986) and Hilborn and Mangel (1996).

Experimental Protocol for Adaptive Management

For all experiments, whether passive or active, the general protocol should be as follows:

1. **Model the system in terms of current understanding and speculation about system dynamics** and use the model to explore issues, such as the magnitude of effects that will derive from particular manipulations, how uncertainty affects outcomes, efficiency of various experimental designs, and the value of information about alternative dynamics. Models of the system may suggest that the most efficient approach is large-scale intervention, pilot or demonstration projects, targeted research, or some combination of these.

2. **Design the management intervention to maximize benefits in terms of both conservation and information.** Where the modeling of management options suggests that more research is needed before any intervention should be attempted, other management measures may be necessary in the short term to ensure that endangered species do not suffer further declines.

3. **Implement management and monitor system response.** In the case of large-scale manipulations, this must go beyond merely monitoring the response variables of interest

(e.g., fish abundance) to provide a report at the end on whether they changed in the desired direction. Monitoring, modeling, and analysis, perhaps together with targeted research, must be designed specifically to determine the extent to which the manipulation affected the variable of interest.

4. **UPDATE PROBABILITIES OF ALTERNATIVE HYPOTHESES** based on analytical results and, if necessary, adjust management policy.

5. **DESIGN NEW INTERVENTIONS BASED ON IMPROVED UNDERSTANDING.**

The experimental protocols for adaptive management are described in further detail in Chapter 3.

ADDRESSING POLITICAL, REGULATORY AND ECONOMIC UNCERTAINTY

The large scope of the ERP requires that it be implemented in stages over the course of several decades. Staged implementation facilitates an adaptive management approach by allowing resource managers to evaluate actions implemented early so that future restoration will benefit from the knowledge gained. It also allows restoration costs to be spread over several years.

Owing to the long implementation timeframe for the ERP, the ecosystem-based, adaptive management process must account for uncertainty produced by non-biological factors in addition to the ecological uncertainty inherent in restoring complex ecosystems. During the projected implementation period for the CALFED Program, there will be approximately eight presidential and gubernatorial elections. These state and national elections will inevitably affect the way existing public policies and programs are interpreted and implemented. Changes in administrations could lead to new state or federal laws, regulations, and programs relating to the regulation and management of water resources, endangered/threatened species, habitat, and ecosystem protection. Current debates concerning the need for new species listings, legal challenges to federal policies (such as Habitat Conservation Plans [HCPs], the "No Surprise" Rule and "Safe Harbor" provisions), and legal challenges to California's Natural Community Conservation Planning Act (NCCPA) process, reflect the potential for changes in law, regulation, and policy that could affect implementation of the ERP and the overall CALFED Program.

Similarly, the volatile nature of global economics has the potential to affect federal, state, and regional budgets and incomes. Fluctuations in the business cycle could ripple into the implementation of the ERP by affecting the funding available for ecosystem restoration or the demands placed upon Bay-Delta resources. The flexibility of an adaptive management approach can allow resource managers to respond to such external forces in much the same way that they respond to new information or unforeseen environmental events.

ONE BLUEPRINT FOR ECOSYSTEM RESTORATION

A single blueprint for ecosystem restoration and species recovery in the Bay-Delta System is a key ingredient for a successful and effective restoration program. Such a blueprint can be the vehicle for ensuring coordination and integration; not only within the CALFED Program, but between all resource management, conservation, and regulatory actions affecting the Bay-Delta System.

A single blueprint represents a unified and cooperative approach defined by three primary elements:

1. integrated, shared science and a set of transparent ecological conceptual models which provide a common basis of understanding about how the ecosystem works;

2. a shared vision for a restored ecosystem ; and

3. a management framework that defines how management and regulatory authorities affecting the Delta will interact and how management and regulatory decisions (including planning, prioritization, and

implementation) will be coordinated and integrated over time.

The integrated science and ecological conceptual models provide a common basis of understanding about how the ecosystem works. These elements, which include competing hypotheses and models, represent the foundation for transparent decision making based upon sound science. This is not to imply that these models are fixed, as they will be tested and modified over time in response to new information in accordance with the principles of adaptive management as part of the CALFED Science Program. Rather, the models represent a basis for guiding management and regulatory decisions at a given point in time. They also provide the rationales for these decisions.

The shared vision of ecological restoration serves to define the desired outcome. While each of the management and regulatory programs have their own distinct set of goals, establishing a unified approach requires that in meeting these goals the various programs also contribute to meeting common goals with respect to ecosystem restoration. The goals for ecological restoration and species conservation established in the ERP and MSCS provide a broad set of goals that provide the common vision for the single blueprint concept.

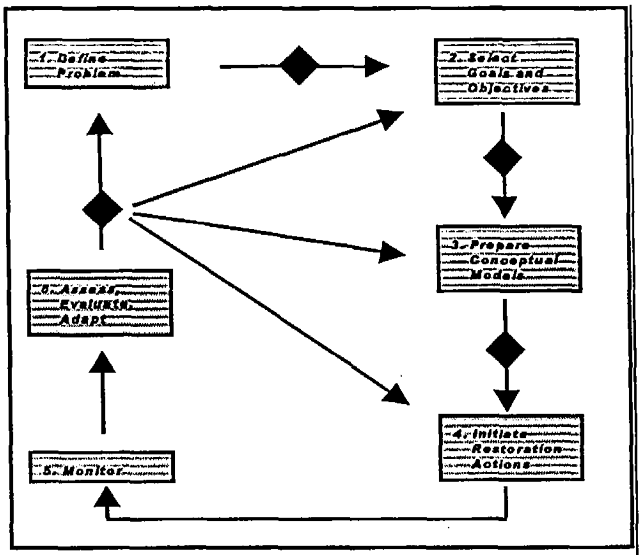
The management framework defines how parties will interact and how management and regulatory decisions will be coordinated and integrated over time. The management framework is designed to foster coordinated and consistent decision making over time. This management framework must be flexible, incorporating and responding to new information and changing Bay-Delta conditions. The framework must be designed to promote coordinated planning, prioritization, and implementation. It must also incorporate provisions for resolving management and regulatory conflicts that may arise.

BENEFITS OF A SINGLE BLUEPRINT

The benefits of a single blueprint approach include the following:

- improved understanding, both of the consequences of certain actions and why specific actions are undertaken;
- increased probability of achieving the desired level of ecosystem health for the Bay-Delta system;
- cost effectiveness;
- avoiding and/or reducing the potential for conflicts that could be counterproductive;
- providing greater management and regulatory certainty; and
- increased support for the program and program funding.

♦ CHAPTER 3. THE ADAPTIVE MANAGEMENT PROCESS



This chapter describes a stepwise procedure that will help incorporate adaptive management in the restoration and management of the Bay-Delta ecosystem. The succeeding discussion describes the steps involved in an adaptive management process, and Figure 3-1 illustrates the process.

DEFINING THE PROBLEM

The first step of an adaptive management process requires clearly defining a problem or set of problems affecting ecosystem health. Defining a problem usually requires determining the geographic bounds of the problem; the ecological processes, habitats, species, or interactions affected by the problem; and the time that the problem affects the ecosystem. Volumes I and II of the ERPP define problems that affect the health of the Bay-Delta ecosystem.

DEFINING GOALS AND OBJECTIVES

Once a problem has been bounded, it is necessary to articulate clear restoration goals and tangible, measurable objectives to provide direction to restoration efforts and to measure progress. Objectives must be tangible and measurable so that progress toward achieving them can be clearly assessed. For example, the following objective statement is too vague: "Improve the quality of habitat for winter-run chinook salmon." By contrast, a more specific statement is: "Restore flows and accessibility of Battle Creek to winter-run chinook salmon spawning within 7 years." Although objectives may sometimes be stated broadly, they must ultimately be made specific through models and hypotheses that translate the objectives into restoration actions.

The Strategic Plan defines broad goals and objectives for the Bay-Delta ecosystem in Chapter 4. Volume II of the ERPP defines targets and programmatic actions for the ecological management zones and units that comprise the larger Bay-Delta ecosystem.

DEVELOPING CONCEPTUAL MODELS

Many resource managers, scientists, and stakeholders interested in the restoration and management of the Bay-Delta ecosystem have *implicit* beliefs about how the ecosystem functions, how it has been altered or degraded, and how various actions might improve conditions in the system. That is, they have simplified mental illustrations about the most critical cause-and-effect pathways. Conceptual modeling is the process of articulating these implicit models to make them explicit.

Conceptual models can provide several benefits. The knowledge and hypotheses about ecosystem structure and function summarized in conceptual models can lead directly to potential restoration actions. They can highlight key uncertainties where research or adaptive probing might be necessary. Alternative, competing conceptual models can illustrate areas of uncertainty, paving the way for suitably-scaled experimental manipulations designed to both restore the system (according to more widely accepted models) and explore it (to test the models). Conceptual models can also help to define monitoring needs, and they

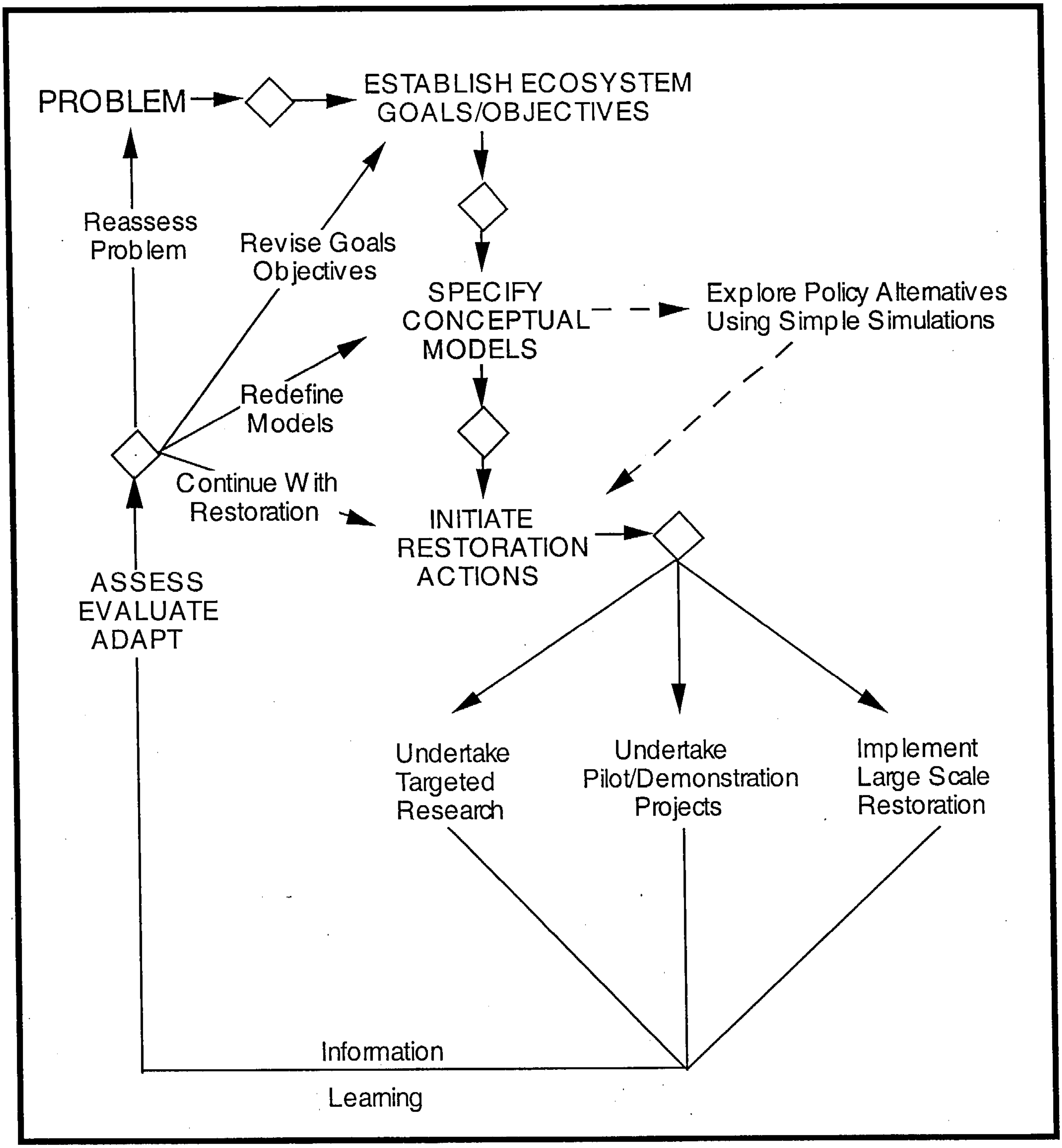


Figure 3-1: Diagram of the Adaptive Management Process.

can also provide a basis for quantitative modeling. Articulating conceptual models can also facilitate dispute resolution since differences between implicit conceptual models often underlie disagreements about appropriate restoration actions.

Conceptual models often suggest many possible restoration actions. In evaluating alternative actions, it is usually very helpful to conduct exploratory simulation modeling based on the conceptual models (Figure 3-1). These simulations are not intended to capture the complexity and richness of ecological processes, but to capture the essential elements of ecological structure and function that underlie management decision making. They are greatly simplified, clear caricatures of the system, just as the conceptual models are clear caricatures. Their purpose is to allow explicit exploration of the main pathways of causal interaction and feedback processes in the conceptual models and provide preliminary predictions of the consequences of different management actions. The simple simulations can aid the decision-making process in many ways. For example, simulation modeling can:

- identify logical inconsistencies in the conceptual models,
- clarify where the nodes of greatest uncertainty are in the conceptual models and where new information would be most useful to decision making,
- allow comparison of the benefits and costs of alternative models of the system and alternative management actions,
- provide a basis for determining how much of a particular kind of restoration action will be required to achieve measurable benefits within a specified period of time,
- provide a basis for determining the value to the ecosystem of new information that might be obtained through adaptive experimentation, and
- help communicate to a broader audience the current understanding of the problem and the explicit rationale for particular restoration measures or targeted research.

Developing Conceptual Models

Conceptual modeling: the process of articulating implicit models (simplified mental illustrations about the most critical cause-and-effect pathways) to make them explicit

- summarize knowledge and hypotheses about ecosystem structure and function
- highlight key uncertainties where research or adaptive probing might be necessary

Exploratory Simulation Modeling: to allow explicit exploration of the main pathways of causal interaction and feedback processes in the conceptual models

- greatly simplified, clear caricatures of the system
- provide preliminary predictions of the consequences of different management actions

Quantitative Modeling: to refine conceptual models or simulation models themselves when a more detailed evaluation of potential alternatives is required

Quantitative modeling may also be a helpful tool to refine conceptual models or simulation models themselves when a more detailed evaluation of potential alternatives is required (Figure 3-1).

Conceptual models are based on concepts that can and should change as monitoring, research, and adaptive probing provide new knowledge about the ecosystem. When key concepts change, the conceptual models should be updated to reflect those changes, thereby paving the way toward changes in management. This will not happen by itself but must be accomplished through a systematic, periodic (e.g., every 3 years) reevaluation of the conceptual models.

An Example of Conceptual Models

There is no recipe for developing conceptual models; nor is there a template for what they should look like. There is no unique set of conceptual models that provides a basis for ecosystem restoration and that can be determined deductively. Conceptual models should be designed for a particular purpose and should contain only those elements relevant to solving a particular problem, including alternative explanations that might yield alternative solutions. The models presented below and in Appendix B are, therefore, simply illustrations of such models and their uses

This section provides an explicit example of a conceptual model (the effects of freshwater flow on fish and invertebrates in the upper estuary) to illustrate the ways such models can be used. Several additional examples of conceptual models are described in Appendix B. The models presented here and in the appendix cover the hierarchy of spatial scales important to ecological restoration, from the landscape scale to the scale of specific ecological processes.

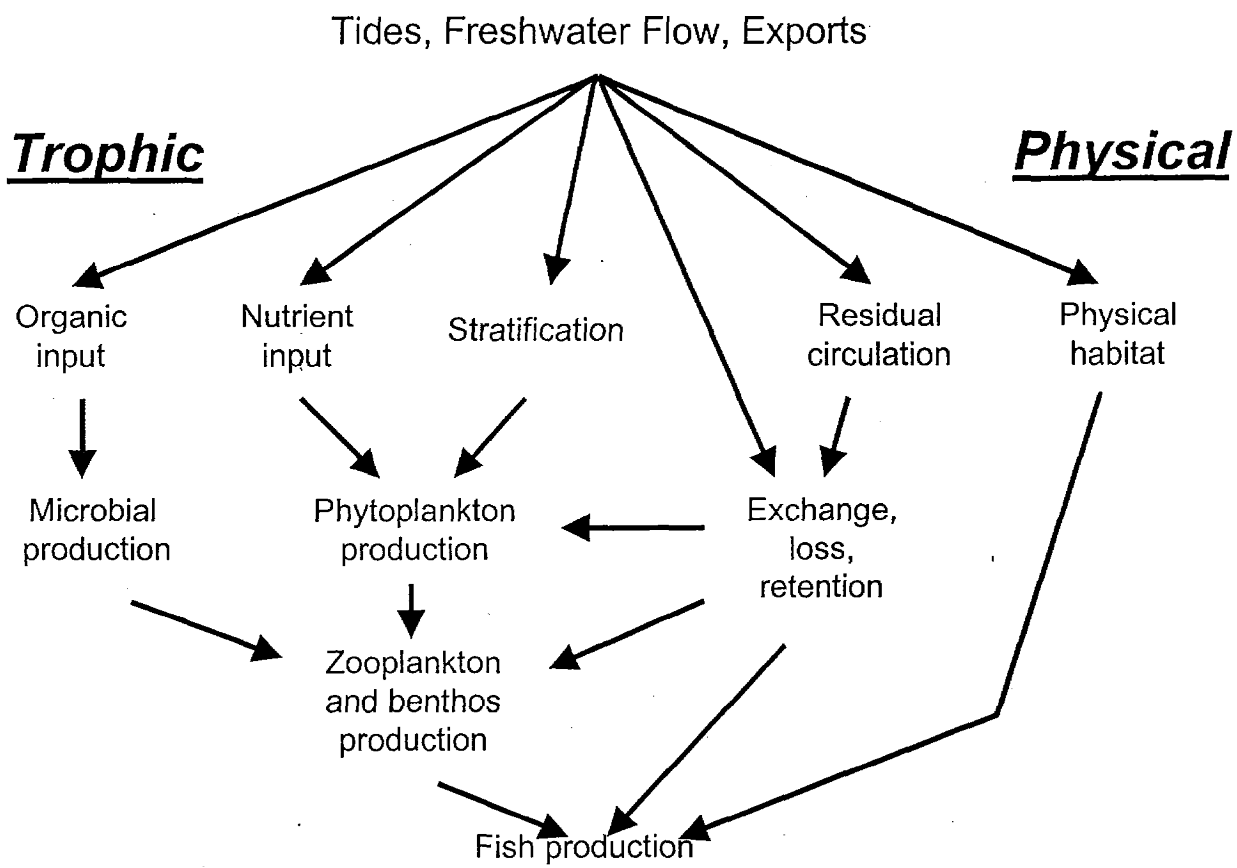
In the "Fish-X2" relationships (Jassby et al. 1995), abundance or survival of several estuarine and anadromous species is related to X2, the distance up the axis of the estuary at which daily average near-bottom salinity is 2 practical salinity units (psu). Because X2 is controlled by freshwater outflow from the Delta, it varies with both inflow and export flows. However, the relationship is entirely empirical and provides no indication of the mechanism controlling abundance or survival. The principal issue addressed here is how different concepts of the mechanism underlying the Fish-X2 relationship define different management tools for maintaining or enhancing populations of estuarine species.

Figure 3-2 illustrates the diverse mechanisms that could account for the X2 relationship for different species. The principal causative variables are freshwater flow and exports, both controllable at least to some extent, and tides, which are not under human control. Briefly, the relationships could arise (as similar ones do in estuaries in other parts of the world) as a result of stimulation of growth at the bottom of the food chain, which then propagates upward, eventually to fish. On the other hand, evidence from this estuary suggests that two kinds of direct physical effects on fish are the more likely mechanisms (Kimmerer 1998). First, flow conditions in the estuary set up by tides and freshwater input, and in some cases by export flows, may alter the retention of some species in the estuary, thereby affecting population size. Second, the amount of physical habitat may change with freshwater flow through such effects as inundation of floodplains or expansion of low-salinity shallow water habitat.

Now consider how potential management interventions are affected by these three scenarios. If the mechanism is stimulation at the base of the food chain, appropriate management actions include addition of nutrients or organic matter to the estuary. If retention is the issue, flows could be manipulated to lengthen or shorten the period of retention in the estuary. If habitat is the issue, physical restoration of habitat or judicious use of flow to increase the amount of habitat at critical times might be in order.

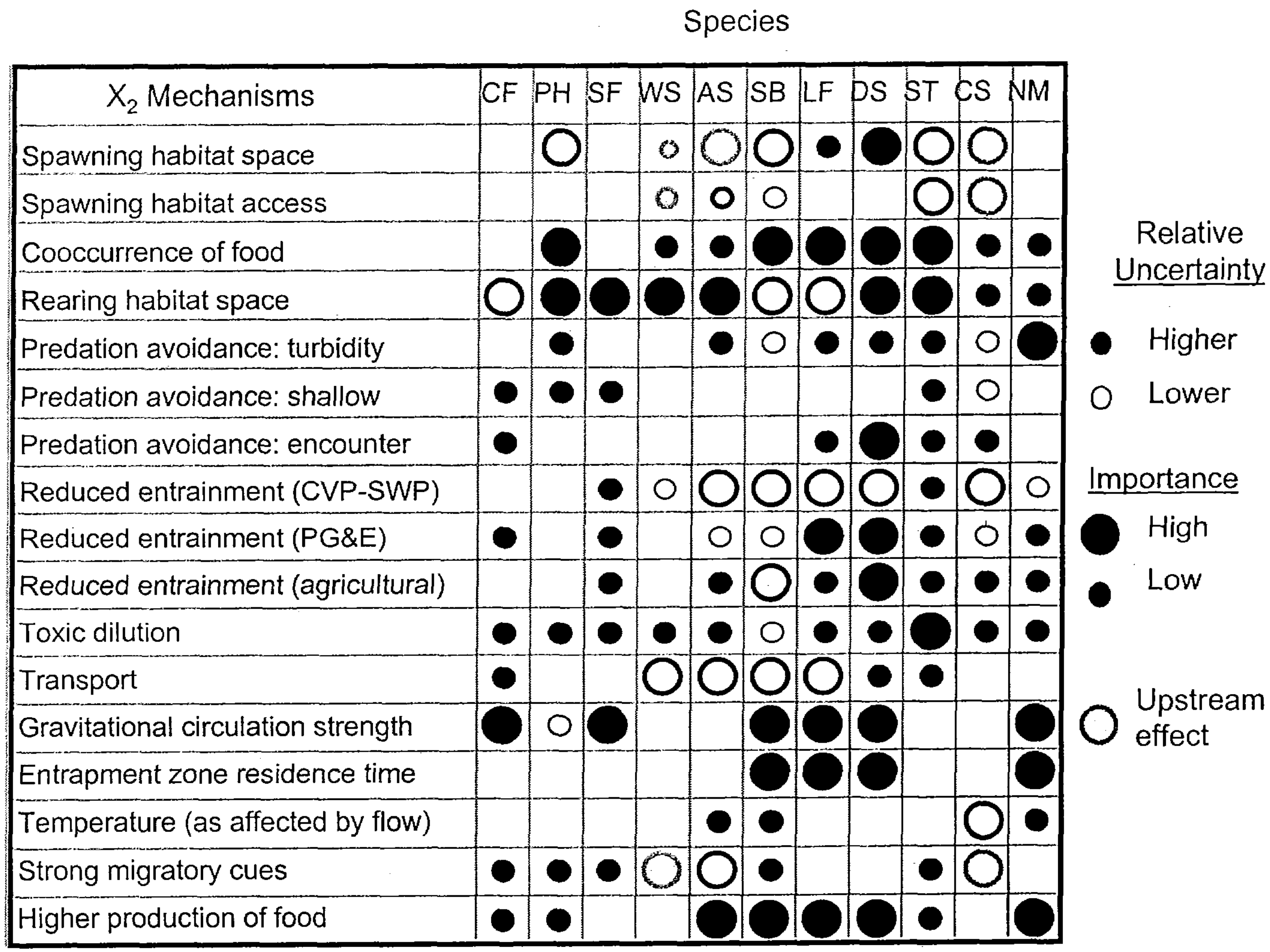
Thus, a very simple model illustrates how critically the management options depend on the assumed cause-and-effect mechanism as well as how various kinds of management interventions can be suggested by a conceptual model. To provide further detail, we use part of the Estuarine Ecology Team's report on the Fish-X2 relationships (Estuarine Ecology Team 1997). That report included a matrix (Figure 3-3) that summarized knowledge about each of the potential mechanisms underlying the Fish-X2 relationships. For each mechanism and each species, the importance of the mechanism is denoted by the size of the symbol. In addition, open symbols denote mechanism for which there is some scientific information, and closed symbols denote mechanisms about which virtually nothing is known.

Each of the mechanisms has a precise definition (Estuarine Ecology Team 1997), but we consider only a few of them here. First, examine the row labeled "Reduced Entrainment (CVP-SWP)." In addition to a number of smaller symbols, large open symbols are given for all the anadromous species except for splittail. Thus, the Estuarine Ecology Team believed that for these species, entrainment could explain at least part of the observed Fish-X2 relationships. Now examine the row labeled "Gravitational Circulation Strength." There are six large filled circles, including those for species that recruit from the ocean as well as several for those that move down-estuary during development and then reside primarily in Suisun or San Pablo Bay and the Delta. In this case, the



Note: The labels "trophic" and "physical" indicate that causative pathways on the left side of the diagram are more biological, based on feeding relationships, whereas those on the right side describe mechanisms that arise through interactions with physical conditions and abundances of species of interest. Tides, freshwater flow, and exports influence organic and nutrient inputs, stratification and gravitational circulation, and the extent of physical habitat with various characteristics. Organic and nutrient input can stimulate growth at the bottom of the food web, which may progress to higher trophic levels, such as fish. Export flow, together with residual and tidal circulation in the estuary, may interact with behavior to affect losses from the estuary or, alternatively, retention. Thus, fish may benefit from increased flow through increased food supply, improved retention in their habitat, or an increase in the quantity or availability of physical habitat.

Figure 3-2: Schematic Diagram Showing Potential Causative Pathways Underlying the "Fish-X2" Relationships



Note: Symbols indicate a potential mechanism according to the key at right. Several minor mechanisms have been eliminated to simplify the diagram. "Upstream" effects refer to flow effects that occur entirely upstream of the Delta. The species abbreviations are defined as follows:

CF = bay shrimp, *Crangon franciscorum*
PH = Pacific herring
SF = starry flounder
WS = white sturgeon
AS = American shad
SB = striped bass
LF = longfin smelt
DS = delta smelt
ST = splittail
CS = Chinook salmon (note: few major effects are in the Delta)
NM = *Neomysis* and other mysids

Figure 3-3: Estuarine Ecology Team's Summary of Potential Causes Underlying "Fish-X2" Relationships team believed gravitational circulation to be an important mechanism although there was virtually no specific information on its effects. Similarly, "Rearing Habitat Space" was considered an important probable mechanism for the largest number of species although knowledge of this topic is limited. In these latter two examples, the Estuarine Ecology Team was exercising professional judgment in the absence of hard scientific information. Similar kinds of judgments will have to be made in decisions about ecological restoration. However, by employing adaptive management, we will be able to design restoration and management actions that allow us to learn about the mechanisms governing ecological function and species abundance while restoration is proceeding.

DEFINING RESTORATION ACTIONS

Conceptual models help to shape the character of restoration actions by identifying key uncertainties or by revealing the level of confidence that a particular action will achieve a given objective. Three types of management actions can be selected for implementation (Figure 3-1). **TARGETED RESEARCH** may be necessary to resolve critical issues about ecosystem structure and function that preclude us from even defining problems adequately. **PILOT OR DEMONSTRATION PROJECTS** can help to determine the practicality or effectiveness of restoration actions, allowing resource managers to evaluate alternative actions or build confidence in the ability of a particular action to achieve an objective. For those restoration actions about which we are reasonably confident will achieve an objective, we can begin **FULL-SCALE IMPLEMENTATION.**

These three types of actions are not mutually exclusive, and all might be used to address a particular problem. Furthermore, they are a set of options and not necessarily progressive.

MONITORING RESTORATION ACTIONS

It is critical to monitor the implementation of restoration actions to gauge how the ecosystem responds to management interventions. Monitoring provides the data necessary for tracking ecosystem health, for evaluating progress toward restoration goals and objectives, and for evaluating and updating problems, goals and objectives, conceptual models, and restoration actions. Monitoring requires measuring the abundance distribution, change or status of ecological indicators.

Ecological indicators are measures of ecological attributes, populations, or processes that can be measured. Indicators include:

- response variables, such as abundance of important species, used to assess trends and measure progress;
- input variables that can be manipulated directly, such as salinity and temperature;
- summaries of habitat characteristics, such as dimensions of river meanders or area of tidal marsh habitat, that indicate progress toward a goal;
- other variables, such as birth, survival, or migration rates, that can be used to interpret the other data and assess the effects of particular manipulations; and
- intermediate variables that may help to understand the trajectory of response variables and some of which might eventually serve to indicate ecosystem condition (e.g., primary or secondary production, inputs or turnover rate of organic carbon or nutrients, or aspects of foodweb structure).

Ecological indicators should based on goals and objectives, and on important elements of conceptual models. Indicators will need to be reevaluated as the system develops and as models change.

EVALUATING AND REVISING PROBLEMS, CONCEPTUAL MODELS, AND RESTORATION GOALS, OBJECTIVES, TARGETS AND ACTIONS

As we learn more about the ecosystem, it is important that this new information feed back into